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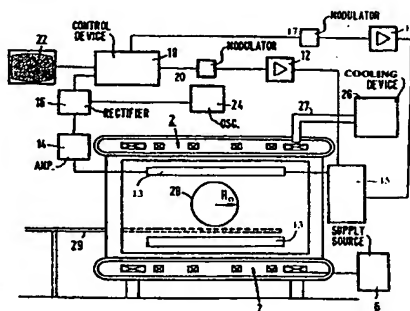
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D-81675 München (DE)(54) **Apparatus and method for spatially ordered phase encoding and for determining complex permittivity in magnetic resonance by using superimposed time-varying electric fields.**

(57) An MRI apparatus of the invention comprises a magnet system for producing a homogeneous magnetic field along the z axis. A plurality of wire conductors are arranged in a "bird cage" or "squirrel cage" configuration and are supplied with a circularly rotating RF field centered near the Larmor frequency ω_0 . The wire conductors also receive a voltage source V_p having a frequency ω_p , which is less than the Larmor frequency. The voltage source V_p is rotated about the wire conductors at a frequency of ω_s , which is much less than the frequency ω_p , to successively apply the voltage V_p to each pair of diametrically opposed wire conductors in a manner which is ordered as a spatial cylindrical harmonic rotating at a frequency ω_s . The voltage source V_p produces electric fields in the object which, in turn, generate linear magnetic field gradients in the object. The voltage source V_p phase encodes the signals detected from the object which thereby enables a transverse magnetization at each point within the object to be rapidly mapped back by projection techniques. Alternately, the transverse magnetization can be mapped back by an inverse transformation of a complex plane extending from the measured region by analytic continuation or by a linear transformation utilizing the solutions to Sommerfeld's Integral. Also, the complex permittivity or ionic mobility may be continuously measured through its effect on the transverse magnetization for analysis or process control. With the invention, an image of the object is rapidly and continuously produced without requiring the use of the conventional gradient field coils and without any mechanical moving parts.

**FIG. 4**

This invention is generally concerned with magnetic resonance imaging (MRI) and, more particularly, to the formation of gradient fields in an imaging volume.

A prior art MRI apparatus, such as that depicted in Fig. 1 and disclosed in U.S. patent No. 4,952,878, which is hereby incorporated by reference, is comprised of a magnet system 2 and a magnet supply source 6 for generating a homogeneous stationary magnetic field H_0 . A magnet system 4 and a supply source 8 generate magnetic gradient fields and an RF coil 10, connected to an RF amplifier 12, generates a radio frequency alternating magnetic field.

The uniform magnetic field H_0 produced by the magnet system 2 and the magnet supply source 6 is formed within an imaging volume along a z axis and causes the nuclei within the object to tend to be aligned along the z axis. The nuclei precess about the z axis at their Larmor frequencies according to the following equation:

$$\omega_0 = \gamma H_0 \quad \text{EQ. (1),}$$

where ω_0 is the Larmor frequency at a field strength of H_0 and γ is the gyromagnetic ratio. The gyromagnetic ratio γ is a constant and is a property of the particular subatomic particle. For instance, the gyromagnetic ratio γ for water protons is 4.26 kHz/gauss. Thus, in a 1.5 Tesla polarizing magnetic field H_0 , the resonant or Larmor frequency of water protons is approximately 63.9 MHz.

In a typical imaging sequence, the RF coils 10 are used to generate an RF signal centered at the Larmor frequency ω_0 . In conjunction with this RF signal, a magnetic field gradient G_z is generated with the gradient coils 4 so that only the nuclei in a selected slice through the object along the x-y plane, which have a resonant frequency centered at the Larmor frequency ω_0 , are excited and absorb energy. Next, the gradient coils 4 are used to produce magnetic field gradients along the x and y axes. Generally speaking, the x axis gradient G_x spatially encodes the precessing nuclei continuously by frequency and the y axis gradient G_y is used to pulse phase encode the nuclei.

The RF coils 10 may be formed in the design of a "bird-cage" or a "squirrel cage" as shown in Fig. 2. Other RF coil designs are also known, such as those disclosed in U.S. Patent No. 4,717,881, U.S. Patent No. 4,757,290, U.S. Patent No. 4,833,409, U.S. Patent No. 4,916,418, U.S. Patent No. 5,017,872, U.S. Patent No. 5,041,790, U.S. Patent No. 5,057,778, and U.S. Patent No. 5,081,418. The RF coils 10 generate a circularly polarized RF field which rotates near the Larmor frequency over the antenna wires 30 of the coil. The RF coils 10 are also used to detect signals from the object and to pass the detected signals onto a signal amplifier 14, a phase-sensitive rectifier 16, and to a control device 18.

A description of the above process is given in more detail below. The spins of the nuclei have an angular momentum \vec{S} which is related to their magnetic moment $\vec{\mu}$ through the gyromagnetic ratio γ , by the equation:

$$\vec{\mu} = \gamma \vec{S} \quad \text{EQ. (2).}$$

With reference to Fig. 3, a single nucleus 1 has a magnetic moment $\vec{\mu}$. All of the spins are subjected to a total ambient magnetic field \vec{H} defined by the equation:

$$\vec{H} = \vec{i}h_x + \vec{j}h_y + \vec{k}(H_0 + h_z) \quad \text{EQ. (3).}$$

As a result of the total magnetic field \vec{H} , a torque \vec{T} is produced on each spin. With reference to Fig. 3, the total magnetic field \vec{H} produces a torque \vec{T} on the nucleus 1 to cause the nuclei 1 to precess. The torque \vec{T} produced is defined by the following equation:

$$\vec{T} = \vec{\mu} \times \vec{H} = \frac{d\vec{S}}{dt}$$

$$\text{EQ. (4).}$$

Substituting and rearranging from the above equations yields:

$$\frac{d\bar{\mu}}{\bar{\mu}} = \left(\frac{\bar{\mu}}{\bar{\mu}} \times \gamma \bar{H} \right) dt$$

EQ. (5),

or,

$$d\bar{\Phi} = (\bar{\Phi} \times \gamma \bar{H}) dt \quad \text{EQ. (6).}$$

From equation (6), it is evident that the differential spatial phase increment $d\bar{\Phi}$ of each spin is related to a cross product of the direction of each spin $\bar{\Phi}$ with the ambient magnetic field \bar{H} multiplied by the gyromagnetic constant γ .

Substituting from the above equations yields:

$$d\bar{\Phi} = (\bar{\Phi} \times \gamma (\bar{i}h_x + \bar{j}h_y))dt + (\bar{\Phi} \times \gamma \bar{k}(H_o + h_z))dt \quad \text{EQ. (7),}$$

or

$$d\bar{\Phi} = d\bar{\theta} + d\bar{\phi}$$

EQ. (8),

where $d\bar{\theta}$ is the differential increment of spatial phase of the precession of $\bar{\mu}$ about an axis perpendicular to the z axis and $d\bar{\phi}$ is the differential increment of the spatial phase of the precession of $\bar{\mu}$ about the z axis.

Therefore, the time-varying angular relationship of each magnetic moment $\bar{\mu}$ is controlled by the applied ambient magnetic field \bar{H} .

A differential increment $d\bar{\theta}$ of $\bar{\mu}$ is produced when $\bar{i}h_x + \bar{j}h_y$ rotates synchronously with $\bar{\Phi}$ at the Larmor frequency. Often, the RF coils 10 are used to create such a circularly polarized RF magnetic field which rotates at the Larmor frequency ω_o by selectively choosing the values of $\bar{i}h_x + \bar{j}h_y$. As a result, an interaction energy W_m is transferred to the spins and is given by:

$$dW_m = -\bar{T} \cdot d\bar{\theta} = -(\bar{\mu} \times \bar{k}(H_o + h_z)) \cdot d\bar{\theta} \quad \text{EQ. (9),}$$

$$W_m = \mu(H_o + h_z)(\cos\theta - 1) \quad \text{EQ. (10).}$$

If the spins are coupled to the surrounding medium to permit relaxation to the minimum energy W_m state before the application of $\bar{i}h_x + \bar{j}h_y$, then the average value of $\bar{\theta}$ for a discrete volume of spins will be at a minimum. The vector sum of each of the magnetic moments $\bar{\mu}$ in a discrete volume will then produce a net magnetization \bar{M} aligned with the z axis. The precessions of the spins $\bar{\theta}$ produced by $\bar{i}h_x + \bar{j}h_y$ about an axis perpendicular to the z axis will give the net magnetization \bar{M} a transverse component \bar{M}_T with a spatial phase ϕ . The strength of the transverse magnetization \bar{M}_T is a function of the number of spins in each discrete sample volume and of the previous excitation and relaxation history of these spins. The transverse magnetization \bar{M}_T is a component of the intensity of a total rotating flux density \bar{B}_T through the permeability of free space μ_o where:

$$\bar{B}_T = \mu_o (\bar{i}h_x + \bar{j}h_y + \bar{M}_T) \quad \text{EQ. (11).}$$

If an antenna loop is placed with its area vector perpendicular to the z axis, it will have a voltage induced in it which is proportional to the time derivative of \bar{B}_T and also a function of the geometry of the conducting antenna loop and of the spatial distribution of the discrete sample volumes, each containing a singular value of \bar{B}_T . This functional dependance is given by the Maxwell-Faraday equation and the vector reception field of the antenna geometry, which may be determined by experimentation.

The transverse magnetization \bar{M}_T has an instantaneous rotational frequency:

$$\frac{d\phi}{dt} = \gamma (H_o + h_z) \triangleq \omega_o + \omega_z$$

EQ. (12)

$$\omega_o \triangleq \gamma H_o; \quad \omega_z \triangleq \gamma h_z$$

EQ. (13).

A polar vector field \vec{G} is defined as the gradient of h_z and is determined according to the following equation:

$$\vec{G} = \nabla h_z = \vec{i} \frac{\partial h_z}{\partial x} + \vec{j} \frac{\partial h_z}{\partial y} + \vec{k} \frac{\partial h_z}{\partial z}$$

EQ. (14).

As discussed above with reference to Fig. 1, the gradient magnets 4, or other type of "gradient coils," provide a spatial address for each discrete component of the imaging volume. The polar vector field \vec{G} , having components G_x , G_y , and G_z defined by Equation 14, is successively incremented by driving the gradient coils over a longer pulse interval or by incrementing the amplitude of the driving current. The signal from the imaging volume is analyzed by Fourier transformation or other integral transformation, to produce a mathematical representation of the spatial address of the transverse magnetization \vec{M}_T in the complex plane.

A problem with many prior art MRI systems, however, is that the time needed to produce the image is relatively long, for instance about 6 minutes. During this time the object to be imaged, for instance the patient, must remain motionless.

The prior art MRI systems are also at a disadvantage due to the manner in which gradient fields are produced. Gradient field generating systems, such as the supply system 8 and the gradient magnet system 4 of Fig. 1, must be able to quickly pulse large currents while precisely controlling the magnitudes of these currents. The pulsing of the large currents produces a pounding noise which often times must be blocked out with earplugs. Although many types of MRI pulse sequences can help reduce the time needed to scan an image, the circuitry in these supply systems becomes extremely complex as well as very costly, in order to provide precise control of large currents.

An additional problem with many MRI systems is that they are unable to generate rotating gradient fields that are sufficiently linear for projection reconstruction image acquisition techniques. Thus, these MRI systems are incapable of producing images by techniques such as projection reconstruction, but must instead rely upon a two or three dimensional truncated Fourier series and the Fourier transformation to produce an image.

The prior art MRI systems further suffer from a disadvantage in that the gradient fields are only produced to a first order approximation of the desired linear gradient fields. Because the gradient fields produced only approximate the desired linear fields, some of the image reconstruction systems used in the prior art systems suffered as a result.

Accordingly, it is an object of the invention to provide an MRI apparatus which overcomes these as well as other problems in the prior art.

It is an object of the present invention to provide an apparatus which can produce linear magnetic field gradients.

It is also an object of the present invention to provide an apparatus that produces magnetic field gradients by generating time varying electric fields.

It is a further object of the present invention to provide an apparatus which generates a "real-time" image of an object.

It is another object of the present invention to provide an apparatus which generates an image of an object by projection reconstruction techniques.

It is yet another object of the present invention to provide an MRI apparatus that can generate an image without having to rely upon the two or three dimensional Fourier transformation but which uses alternate methods of processing signals detected from an object.

It is yet a further object of the present invention to provide an apparatus for generating magnetic field gradients which is useful in spectroscopy as well as in other applications involving magnetic resonance.

To achieve the foregoing and other objects, in accordance with the present invention, as embodied and broadly described herein, the apparatus of the present invention comprises a magnet system or other conventional system for generating a homogeneous magnetic field directed along the z axis. A plurality of wires are arranged parallel to each other along the z axis in a typical "bird cage" or "squirrel cage" configuration which is tuned near the Larmor frequency ω_0 .

A circularly polarized RF field centered near the Larmor frequency ω_0 is generated so that it rotates about the wire conductors. A sinusoidal voltage source having a frequency ω_p , which is less than the Larmor frequency ω_0 , is sequentially applied as a spatial cylindrical harmonic across diametrically opposed wire conductors at an angular spatial frequency of ω_s , where ω_s is very much less than the frequencies ω_0 and ω_p .

The electric current density that is generated by the voltage source of frequency ω_p produces a magnetic field in the object that alters the phase of each spin in a periodic and spatially ordered field. The transverse magnetization \bar{M}_T of the nuclei produces an RF signal that is detected by the wire conductors and is then supplied to a control device for signal processing.

The control device can analyze the signal as a high signal to noise rapidly repeated continuous analytic function at the origin of the complex "K" plane by analytic continuation. Also, the control device may analyze the received signals as a continuous set of rapidly rotating views of the sum of the transverse magnetization \bar{M}_T by projection reconstruction. The determination of the transverse magnetization \bar{M}_T may be performed with Bessel functions or with the solution to Sommerfeld's integral, both of which allow the use of look up tables.

The invention can therefore generate the necessary magnetic field gradients by applying time varying electric fields to an RF coil assembly. Thus, the conventional "gradient coils" are no longer a necessity in the formation of images with an MRI apparatus. However, the apparatus of the present invention does not necessarily eliminate the conventional gradient coils since the application of the time varying electric fields may be used in conjunction with the conventional gradient coils. For instance, the gradient fields produced by the electric fields may be used to dephase or enhance some of the phase encoding generated with the conventional gradient coils. As a result of this, the image generated by the MRI apparatus can be made more narrow and thus the apparatus can focus in on a particular region of interest and block out all other regions.

Additional objects, advantages and novel features of the invention will be set forth in the description which follows, and will become apparent to those skilled in the art upon reading this description or practicing the invention. The objects and advantages of the invention may be realized and attained by the appended claims.

The accompanying drawings, which are incorporated in, and form a part of, the specification, illustrate some embodiments of the present invention and, together with the description, serve to explain the principles of the invention. In the drawings:

Fig. 1 is a block diagram of an embodiment of a prior art MRI apparatus;

Fig. 2 is a prior art RF coil assembly;

Fig. 3 is a perspective representation of a precessing nuclear spin;

Fig. 4 is a block diagram of a first embodiment of the invention;

Fig. 5 is an exemplary diagram of the circuitry used for generating the magnetic field gradients by way of electric fields; and

Fig. 6 is a second embodiment of the MRI apparatus of the present invention.

Reference will now be made in detail to the preferred embodiments of the invention, examples of which are illustrated in the accompanying drawings.

With reference to Fig. 4, an MRI apparatus of the invention comprises a magnet system 2 for generating a homogeneous stationary magnetic field H_0 and a supply source 6 for supplying the magnet system 2 with operating power. The magnet system 2 may be of the superconducting type which requires a connection to a cooling device 26 through a cooling duct 27. The invention, however, is not limited to this specific type of magnet system 2 and other types of magnet systems 2, such as permanent magnets or resistive nonpermanent magnets, may alternatively be used.

A phase-sensitive rectifier 16 receives a signal from an oscillator 24 and supplies an output to a control device 18. The control device 18, together with a modulator 20 which is under the control of the control device 18, produces a signal modulated near the Larmor frequency which is amplified with an RF amplifier 12 and then supplied to an interface circuit 15.

The interface circuit 15 may comprise an amplitude and phase control network 42 such as that illustrated in Fig. 2. The interface circuit 15 individually controls the voltages applied to each of a plurality of wires 30 forming part of an RF coil assembly 13. Preferably, the interface circuit 15 generates a circularly polarized RF field having a frequency centered near the Larmor frequency ω_0 and which rotates over the wires 30 of the RF coil assembly 13.

The control device 18, together with a second modulator 17 controlled by the control device 18, also produces a sinusoidal voltage at a frequency of ω_p . This signal is amplified by a low frequency amplifier 19 before being supplied to the interface circuit 15. The interface circuit 15 comprises circuitry 50, shown in diagrammatical form in Fig. 5, for generating electric fields from the sinusoidal voltage. The circuitry 50 comprises a polyphase synchro generator 52 for receiving across its terminals the voltage source V_p , which is preferably a sinusoidal voltage signal equal to $V_p \sin(\omega_p t)$. The polyphase synchro generator 52 rotates at a frequency of ω_s and successively applies the voltage signal V_p to each pair of opposed conductor wires 30 as a spatial cylindrical harmonic function of the rotating frequency ω_s of the primary winding illustrated in Fig. 5.

The coil assembly 13 having the opposed wires 30 may be formed in the conventional "bird cage" or "squirrel cage" configuration, such as that illustrated in Fig. 2. The coil assembly is tuned near the Larmor frequency ω_0 so that the circularly polarized RF field generated near the Larmor frequency ω_0 can rotate about the wires 30. A first set of isolation filters Z_1 are for filtering out the circularly polarized voltages generated near the Larmor frequency ω_0 and are connected between the wires 30 and contact points for the polyphase synchro generator 52. Another set of filters Z_3 are connected between the wires 30 on one ring conductor 34 of the coil assembly 13. These filters Z_3 tune the coil assembly 13 near the Larmor frequency ω_0 so that voltages near the Larmor frequency may rotate about the coil assembly 13 and also prevent other signals, such as the voltage signal V_p , from rotating about the coil assembly 13.

The Larmor frequency ω_0 , the frequency ω_p of the voltage signal V_p , and the frequency ω_s at which the polyphase synchro generator rotates, are selected such that:

$$\omega_0 > \omega_p \gg \omega_s \quad \text{EQ. (15).}$$

The electromechanical polyphase synchro generator configuration 52 is diagrammatic only and is preferably comprised of solid state circuitry. For instance, the polyphase synchro generator 52 may be replaced with an amplitude and phase control network and a voltage divider network that produces a spatial cylindrical harmonic array of sinusoidal voltages having a temporal frequency of ω_p . The voltage divider network may then periodically apply the array of sinusoidal voltages to opposed wire conductors 30 at the angular spatial frequency of ω_s . These voltages are periodically applied over a spatial angle α , where:

$$\alpha = \omega_s t \quad \text{EQ. (16).}$$

Besides using the coil assembly 13 to transmit electromagnetic fields that have frequencies of ω_0 and ω_p , the coil assembly 13 is also preferably used as a receiver to detect RF signals emitted by the nuclei in an object to be imaged. The signals detected with the RF coil assembly 13 are passed through a set of filters Z_2 for filtering out unwanted frequencies and unwanted signals, such as those intended for transmission or phase modulation. The detected signals are amplified with an RF amplifier 14, rectified with rectifier 16, and then processed in the control device 18 in order to construct an image of the object which is displayed on a monitor 22.

The embodiment illustrated in Figs. 4 and 5 does not contain the conventional "gradient coils," such as the gradient coils 4 in Fig. 1. Instead, the embodiment employs an RF coil assembly 13 for transmitting an RF pulse and for also creating the magnetic field gradients. The manner in which these gradients are produced and the manner in which the detected signals are processed will now be presented in more detail below.

As shown by Equation 17, the gradient field \bar{G} is defined to be the gradient of the z component h_z of the magnetic field \bar{H} .

$$\vec{G} = \nabla h_z$$

EQ. (17)

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As a result, with reference below to Equations 18 and 19, the curl of the gradient field \vec{G} must be equal to zero and, using Stokes theorem, the closed line integral of the gradient field \vec{G} must also be equal to zero. Although the curl of the gradient field \vec{G} is equal to zero, the curl of the magnetic field \vec{H} is not equal to zero.

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$$\nabla \times \vec{G} = 0, \text{ (but } \nabla \times \vec{H} \neq 0) \quad \text{EQ. (18);}$$

and

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$$\oint \vec{G} \cdot d\vec{L} = 0 \quad \text{EQ. (19);}$$

where, in a cartesian system of coordinates, the differential path element $d\vec{L}$ is defined as:

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$$d\vec{L} = \vec{i}dx + \vec{j}dy + \vec{k}dz \quad \text{EQ. (20).}$$

Therefore, the relationship between the z component h_z of the applied magnetic field \vec{H} and the gradient field \vec{G} is as follows:

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$$\int_0^x \int_0^y \int_0^z \vec{G} \cdot d\vec{L} = h_{z(x,y,z)}$$

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EQ. (21),

and, assuming cylindrical symmetry,

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$$\frac{\partial h_x}{\partial z} = \frac{\partial h_y}{\partial z} = \frac{\partial h_z}{\partial z} = 0$$

EQ. (22).

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one may therefore conclude that the relationship between the gradient field \vec{G} and the magnetic field \vec{H} is as follows:

$$\vec{G} = \vec{k} \times (\nabla \times \vec{H}) \quad \text{EQ. (23).}$$

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The relationship between the z component h_z of the magnetic field \vec{H} and the applied electric field \vec{E} may also be determined. From one of Maxwell's equations, it is known that the current density \vec{J} is equal to the curl of the magnetic field \vec{H} .

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$$\nabla \times \vec{H} = \vec{J} \quad \text{EQ. (24).}$$

As shown in Equation 25, the total current density \vec{J}_T is comprised of a number of components.

$$\vec{J}_T = \vec{i}J_x + \vec{j}J_y + \vec{k}J_z = \vec{J}_i + \vec{J}_{le} + \vec{J}_{de} \quad \text{EQ. (25);}$$

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where:

\vec{J}_i = impressed (source) electric current density;

\bar{J}_{ie} = effective conductive electric current density = $(\sigma_s + \omega_p \epsilon'') \bar{E}$; EQ. (26)

\bar{J}_{de} = effective displacement electric current density;

$$= j\omega_p \epsilon' \bar{E}; \quad \text{EQ. (27)}$$

ϵ = the complex permittivity ϵ of the medium;
 $= \epsilon' - j\epsilon''$; EQ. (28);

and

σ_s = the static conductivity.

An electric field \bar{E} is defined in exponential terms as follows:

$$\bar{E} = E e^{j\omega_p t}$$

EQ. (29);

where

$$\bar{E} = iE_x + jE_y \quad \text{EQ. (30).}$$

Assuming a source free region, the impressed electric current density \bar{J}_i is zero and the total current density \bar{J}_T is reduced to the form:

$$\bar{J}_T = 0 + (\sigma_s + \omega_p \epsilon'' + j\omega_p \epsilon') \bar{E} \quad \text{EQ. (31).}$$

The total current density \bar{J}_T expressed in more general terms is as follows:

$$\bar{J}_T = C_{(j\omega_p)} \bar{E} = |C| e^{j\psi} \bar{E}$$

EQ. (32).

By using the relationship between the gradient \bar{G} and the z component h_z of the magnetic field \bar{H} (Equation 21) and the relationship between the gradient field \bar{G} and the magnetic field (Equation 23), the z component h_z of the magnetic field \bar{H} may be expressed in terms of the electric field \bar{E} by the following equation:

$$h_{z(x,y)} = |C| e^{j(\omega_p t + \psi)} \left(\int_0^y E_x dy - \int_0^x E_y dx \right)$$

EQ. (33).

Thus, the z component h_z of the magnetic field \bar{H} , which defines the gradient field \bar{G} , may be generated by applying electric fields to the object. The relationship between the desired z component h_z and the electric field \bar{E} , and thus the relationship between the gradient field \bar{G} and the electric field \bar{E} , is determined by Equation 33.

To aid in the understanding of this relationship, consider a uniform electric field \bar{E} produced by a voltage V applied across two large conducting plates. The two conducting plates are perpendicular to the x axis, parallel to the z axis, and are separated by a distance D. The components of the electric fields

produced by this voltage V are then determined according to the following equations:

$$E_x = \frac{V}{D} ; E_y = 0$$

EQ. (34) .

Integrating Equation 12 to solve for the phase ϕ as a function of time, yields the following equation:

$$\phi(t) = \int_0^t \gamma (H_o + h_z) dt$$

EQ. (35) .

Then, substituting the value of the z component h_z of the magnetic field \bar{H} from Equation 33 and solving yields the following in time-harmonic form:

$$\phi(t, y) = \gamma H_o t + y \frac{\gamma |C| V}{\omega_p D} e^{j(\omega_p t + \psi)}$$

EQ. (36) ;

or, in real-time form:

$$\phi(t) = \gamma H_o t + y \frac{\gamma |C| V}{\omega_p D} \sin(\omega_p t + \psi)$$

EQ. (37) .

Since the transverse flux density \bar{B}_T produced by each element in the object having an area of $dx dy$ in the complex x, jy plane is known to be:

$$B_{T(x, y, t)} = \mu_o M_{T(x, y)} e^{j\phi(y, t)}$$

EQ. (38) ,

the voltage induced in the coil assembly 13 by each element of $dx dy$ is:

$$dv_{o(t)} = f_{(x, y)} (\mu_o M_{T(x, y)} e^{j\phi} \frac{d\phi}{dt}) dx dy$$

EQ. (39) .

Integrating this equation and solving for the induced voltage yields:

$$v_o(t) = \int_{-D/2}^{+D/2} \left(\int_{-D/2}^{+D/2} f_{(x,y)} \mu_o M_{T(x,y)} dx \right) (e^{j\phi} \frac{d\phi}{dt}) dy \triangleq \int_{-D/2}^{+D/2} A_{(y)} B_{(y,t)} dy$$

EQ. (40).

In Equation 40, $v_o(t)$ is the output voltage detected by the coil assembly 13 which is analyzed by the control device 18. The element $B_{(y,t)}$ in Equation 40 is a phase modulating function of space and time which is also determined by the control device 18. Since $v_o(t)$ and $B_{(y,t)}$ are known variables, Equation 40 may be solved to determine element $A_{(y)}$ and thus the projection of the transverse magnetization \bar{M}_T .

This yields one view of a projection-reconstruction of the image. If Equation 40 is subject to a complex spatial transformation, such as the Fourier transformation, an analytic continuous segment in the complex "K" plane may be determined.

Up to this point, the transverse magnetization \bar{M}_T has been determined as if the electric fields have been generated from two parallel conducting plates. Since the embodiment of Fig. 4 has a plurality of wires 30, each pair of opposed wires 30 will approximate a pair of conducting plates for an infinitesimal element in the object. By performing a conformal transformation, which is within the skill of one of ordinary skill in the art, the generalized orthogonal rectilinear space is transformed through the Cauchy-Reimann condition equations to an orthogonal curvi-linear space so that the phase encoding electric field \bar{E} may be produced by an array of conductors arranged parallel to the z axis around the periphery of the object to be imaged. The spatial address of each element \bar{M}_T is also subjected to the same conformal transformation. The purpose of the conformal transformation is to translate the relationships defined by two parallel plate conductors to the relationships which exist in the embodiment of Fig. 4.

Next, by slowly rotating the voltage source V_p about the wires 30 at the spatial angle of α , a continuous set of views of projection reconstruction are generated. Each view is the average of a number of images in time so that the signal to noise ratio is thereby improved. The rotation of the voltage source V_p may also be visualized as generating an "n-leaved rose" pattern of closely spaced lines centered at the origin of the complex "K" plane.

The spatial distribution of \bar{M}_T may be continuously computed to thereby form a virtual "real-time" image while simultaneously applying RF energy to or receiving RF energy from the object to be imaged.

An alternate manner of determining the transverse magnetization \bar{M}_T involves the use of Bessel functions. Turning back to the parallel conducting plates analysis, the phase ϕ as a function of time may be expressed by the following equation:

$$\phi_{(y,t)} = \int_0^t \gamma (H_o + h_z) dt$$

EQ. (41).

After substituting in the expression for the z component h_z of the magnetic field \bar{H} , the phase function ϕ may be expressed in real time as:

$$\phi = \gamma H_o t + y(\gamma) (C) \left(\frac{V}{D} \right) \left(\frac{1}{\omega_p} \right) \sin(\omega_p t)$$

EQ. (42).

Also, the transverse magnetic flux density \bar{B}_T is known to be equal to:

$$B_{T(x,y,t)} = \mu_o M_{T(x,y)} e^{j\phi(y,t)}$$

EQ. (43).

If a coil is placed in the x-z plane, a voltage $v(t)$ will be induced in the coil which is equal to:

$$v(t) = \int_{-D/2}^{+D/2} \left(\int_{-D/2}^{+D/2} f(x,y) \mu_0 M_{T(x,y)} dx \right) \left(\frac{d}{dt} \sin \phi \right) dy$$

EQ. (44).

Since Equation 42 provides an expression for ϕ , $\sin \phi$ in Equation 44 may be expanded to equal:

$$\sin \phi = \sin(\omega_0 t + Ay \sin \omega_p t) \quad \text{EQ. (45).}$$

In Equation 45, the variable A and ω_0 are defined to be:

$$A \triangleq \frac{\gamma CV}{D \omega_p} ; \quad \omega_0 \triangleq \gamma H_0$$

EQ. (46).

Using Bessel functions, the expression $\sin \phi$ may be expressed as:

$$\begin{aligned} \sin \phi = J_0(Ay) \sin(\omega_0 t) + \sum_{n=1}^{\infty} J_n(Ay) \Big[(-1)^{n+1} \sin(\omega_0 + n\omega_p) t \\ + (-1)^n \sin(\omega_0 - n\omega_p) t \Big] \end{aligned}$$

EQ. (47);

and

$$\begin{aligned} \frac{d \sin \phi}{dt} = \omega_0 J_0(Ay) \cos(\omega_0 t) + \sum_{n=1}^{\infty} J_n(Ay) \Big[(-1)^{n+1} (\omega_0 + n\omega_p) \\ \cos(\omega_0 + n\omega_p) t + (-1)^n (\omega_0 - n\omega_p) \cos(\omega_0 - n\omega_p) t \Big] \end{aligned}$$

EQ. (48).

In conventional systems, a free induction decay signal is produced by broadening the absorption line by a conventional gradient coil. The free induction decay signal is the Fourier coefficient of the transverse magnetization \bar{M}_T projected perpendicular to the gradient. In contrast, with the embodiment of Fig. 4, an electric field \bar{E} modulates the phase increment to produce a line spectrum centered at the Larmor

frequency. The amplitudes of the line spectrum are equal to the integral of the projection of M_T taken along the electric field \bar{E} weighted by a Bessel function whose order is the order of each harmonic and whose magnitude is proportional to the position of each element of the projection along the gradient perpendicular to the electric field \bar{E} .

For each harmonic n in the line spectrum, the sum of the upper and lower sideband voltage output detected by the coil assembly is equal to:

$$|V_n| = \int_{-D/2}^{+D/2} P_{(y,n)} J_n(Ay) dy$$

EQ. (49) ,

where:

$$P_{(y,n)} = 2\mu_o n \omega_p \int_{-D/2}^{+D/2} f_{(x,y,n)} M_{T(x,y)} dx$$

EQ. (49a) .

From Equations 49 and 49a. The projection of the transverse magnetization \bar{M}_T may be determined. Once the projection of the transverse magnetization \bar{M}_T has been determined, it is within the capability of one of ordinary skill in the art to generate an image of the object.

A third manner in which the control device 18 may process the detected signals and generate an image of an object is through the use of Sommerfeld's integral. The transverse magnetic field density \bar{B}_T , which is the output detected by the coil assembly 13, is equal to:

$$B_{T(t)} = \mu_o e^{j\omega_o t} \int_{-D/2}^{+D/2} M_{T(y)} e^{-jAys \sin \omega_p t} dy$$

EQ. (53) .

Taking the Fourier transform of the transverse magnetic field density \bar{B}_T , yields the following:

$$G(\omega) = \mu_o \int_{-\infty}^{+\infty} B_{T(t)} e^{-j\omega t} dt = \frac{\mu_o}{j\omega_p} \int_{-D/2}^{+D/2} M_{T(y)} \int_{-\infty}^{+\infty} e^{j(\omega_o - \omega)t} \cdot e^{-jAys \sin \omega_p t} d(j\omega_p t) dy$$

EQ. (54) .

If the following variables are defined accordingly:

$$n \triangleq \frac{(\omega_o - \omega)}{\omega_p} ; \rho \triangleq Ay ; \tau \triangleq \omega_p t$$

EQ. (55) ;

then part of Equation 54 may be abbreviated to Sommerfeld's integral, as shown by the following:

$$G(\omega) = \int_{-D/2}^{D/2} \mu_o \frac{M_T}{j\omega_p} \int_{-j\infty}^{+j\infty} e^{j(\rho \sin \tau - \pi \tau)} d\tau dy$$

EQ. (56) .

Therefore, Equation 54 can be further simplified to the form:

$$G(\omega) = \int_{-D/2}^{D/2} \frac{\mu_o}{j\omega_p} M_{T(y)} \pi Z_n(\rho) dy$$

EQ. (57) ,

where $Z_n(\rho)$ is the solution to Sommerfeld's integral. The frequency content of the voltage detected with coil assembly 13 will determine the variable $G(\omega)$. Also, with every value of y and n , the control device 18 may determine a value of $Z_n(\rho)$ by using well known tables and methods to the various solutions of Sommerfeld's integral. Accordingly, the transverse magnetization M_T can be determined and an image of the object can be generated.

Another embodiment of the invention is illustrated in Fig. 6. As shown in this figure, the MRI apparatus comprises a conventional set of gradient coils 4 and a supply source 8 for generating gradient fields. The MRI apparatus further comprises the circuitry shown in Fig. 4 of the invention, which generates gradient fields by using electric fields. The MRI apparatus of Fig. 6, like the embodiment of Fig. 4, also comprises an interface circuit 15, a modulator 17, and an RF amplifier 19.

The gradient fields produced by the electric fields may be used in the embodiment of Fig. 6 to enhance or dephase some of the gradient fields generated by the conventional gradient coils. This may be advantageous in applications where an image is desired of only a small region of the object. The gradient fields produced by the electric fields would combine with the gradient fields produced by the conventional gradient coils with the resultant gradient fields affecting only that small region in the object. Thus, a more narrow image of the object is produced which reveals only that small desired portion of the object and which deletes all other portions of the object.

The RF coil assembly 13 may also be used to correct for inhomogeneities of the complex dielectric constant and also to correct for anisotropy. These errors may result from an inhomogeneous complex dielectric constant in the object that shifts the "gradient" horizontally in opposite directions, depending upon the polarity of the applied electric field. Thus, the inhomogeneous complex dielectrics distort the magnetic field gradients produced by the RF coil assembly 13 thereby rendering the gradient fields non-linear.

To illustrate how the RF coil assembly 13 may correct these errors, first consider the expression for the phase ϕ , which is:

$$\phi = \gamma H_0 t + \int_0^x \int_0^t (\gamma E C \cos \omega_p t) dt dr$$

EQ. (58) .

Defining a first coordinate system T as being equal to $r + js$, a first detected phase ϕ_1 is equal to:

$$\phi_1(t) = \frac{\gamma \sin \omega_p t}{\omega_p} E_s \int_0^r C_{(r)} dr$$

EQ. (59),

where the variable $C_{(r)}$ is defined accordingly:

$$C_{(r)} \triangleq C + \epsilon_{(r)}$$

EQ. (60),

and

$$C \triangleq \frac{1}{D} \int_{-D/2}^{D/2} C_{(r)} dr$$

EQ. (61).

After substituting in the expression for $C_{(r)}$ into Equation 59, the expression for the first detected phase ϕ_1 becomes:

$$\phi_1(t) = \frac{\gamma \sin \omega_p t}{\omega_p} E_s (Cr + \int_0^r \epsilon_{(r)} dr)$$

EQ. (62).

If we define a second coordinate system W as being equal to $u + jv$, a second detected phase ϕ_2 is equal to:

$$\phi_2(t) = \frac{\gamma \sin \omega_p t}{\omega_p} E_v \int_0^u C_{(u)} du$$

EQ. (63),

where the variable $C_{(u)}$ is defined accordingly:

$$C_{(u)} \triangleq C + \epsilon_{(u)}$$

EQ. (64),

and

$$C \triangleq \frac{1}{D} \int_{-D/2}^{D/2} C(u) du$$

EQ. (65).

Next, after substituting in the expression for $C(u)$ into Equation 63, the expression for the second detected phase ϕ_2 becomes:

$$\phi_2(\tau) = \frac{\gamma \sin \omega_p \tau}{\omega_p} E_v \left(C u + \int_0^u \epsilon(u) du \right)$$

EQ. (66).

If the two coordinate systems T and W are respectively defined by electric fields of opposite polarities, which occur when the applied voltages have opposite polarities, then the following variables in the two coordinate systems are interrelated according to the following expressions:

$$T = -W; r = -u; s = -v; E_s = -E_v \quad \text{EQ. (67).}$$

With Equation 66, the expression for the second detected phase ϕ_2 may be altered to the form:

$$\phi_2(\tau) = \frac{\gamma \sin \omega_p \tau}{\omega_p} (-E_s) \left[C(-r) + \int_0^{-r} \epsilon(-r) d(-r) \right]$$

EQ. (68),

which reduces to the form:

$$\phi_2(\tau) = \frac{\gamma \sin \omega_p \tau}{\omega_p} (E_s) \left[Cr - \int_0^{-r} \epsilon(-r) d(-r) \right]$$

EQ. (69).

Since the following equation is true:

$$\int_0^r \epsilon(r) dr = \int_0^{-r} \epsilon(-r) d(-r)$$

EQ. (70),

the sum of the first detected phase ϕ_1 with the second detected phase ϕ_2 will be equal to:

$$\phi_1 + \phi_2 = 2(E_s) \frac{\gamma \sin \omega_p t}{\omega_p} C r$$

EQ. (71),

which is a corrected phase signal that is not influenced by the error signal. Also, the difference between the first detected phase ϕ_1 and the second detected phase ϕ_2 will equal:

$$\phi_1 - \phi_2 = 2 \int_0^r \epsilon_{(r)} dr$$

EQ. (72),

which separates the error signal from the phase encoded signal.

By subtracting the detected signals when the applied voltages are of opposite polarity to each other, the errors caused by inhomogeneity and anisotropy in the object cancel. Since the corrected signal therefore has less distortion, the image is improved.

An advantage of the present invention is that the costly and complex gradient coils in the conventional MRI apparatus are no longer a necessity since the gradient fields may be produced by the application of a time varying voltage V_p to the RF coil assembly 13. As a result of the time varying voltage V_p , electric fields are generated in the object and produce time varying magnetic fields that have a uniform curl. Consequently, the apparatus of the present invention produces linear magnetic field gradients.

Another advantage of the present invention is that the processing of the detected signals is not limited to the two or three dimensional truncated Fourier series or Fourier transformation. Rather, the apparatus of the present invention may process the detected signals by projection techniques and may use Bessel functions or the solution to Sommerfeld's integral in order to solve for the transverse magnetization \bar{M}_T .

A further advantage of the present invention is that some image artifacts are eliminated. The invention does not produce image artifacts caused by the periodic displacement of spins resulting from the interaction of their charge and mass with the applied electric field, which is a component of the complex permittivity, but is orthogonal to both the z axis and also the gradient field \bar{G} , since no phase dispersions are produced unless another gradient is applied along the direction of the applied electric field. Combining these gradients as in the embodiment of Fig. 6 allows selective dephasing of some of the spins in the imaging volume.

The image may also be improved with the present invention by detecting phase encoded signals when the applied voltages have opposite polarities. By summing together phase encoded signals detected when the applied voltages have opposite polarities, the error components of the signals cancel each other thereby producing a corrected phase encoded signal. The error signal may also be separated from the phase encoded signal by subtracting the two phase encoded signals. The corrected phase encoded signal, since it no longer contains the error signal, has less distortion which thereby produces an improved image of the object.

The foregoing description of the preferred embodiments of the invention has been presented for purposes of illustration and description. It is not intended to be exhaustive or to limit the invention to the precise forms disclosed. Many modifications and variations are possible in light of the above teaching.

For example, although the embodiments have been described with reference to a system that uses RF pulses, the invention is equally applicable to a continuous wave system. Further, rather than applying a voltage V_p which has a constant frequency of ω_p , the frequency of the applied voltage V_p may vary in order to find the resonances of the dispersion of the complex dielectrics of the object and to measure complex dielectrics in the object.

Also, although the electric fields have been used to produce magnetic field gradients for the generation of an image, the electric fields may also be used to generate magnetic field gradients which function to destroy parts of an image. Thus, a more narrow image may be generated which does not reveal portions of the object which are not of interest. The technique of making an image more narrow may be used in spectroscopy to thereby make it possible to tell the number of spins of a particular species. It may also be possible to identify particular species of charged particle mobility with this technique.

Moreover, the generation of magnetic field gradients with electric fields has applications with magnetic resonance other than in just the imaging of an object. For instance, a magnetic resonance apparatus may be used to determine whether fruit is fresh, whether a chocolate bar has been frozen and then thawed, as well as a multitude of other possibilities. The invention is equally applicable to these other magnetic resonance applications.

The embodiments were chosen and described in order to best explain the principles of the invention and their practical application to thereby enable others skilled in the art to best utilize the invention and various embodiments and with various modifications as are suited to the particular use contemplated. It is intended that the scope of the invention only be limited by the claims appended hereto.

Claims

1. An apparatus for generating magnetic field gradients for use in magnetic resonance imaging of an object, comprising:
 - a plurality of conductive wires arranged in parallel to each other and formed in a shape of a cylinder;
 - a first ring conductor for joining said conductive wires at one end of said conductive wires;
 - a second ring conductor for joining said conductive wires at an end opposite said one end of said conductive wires;
 - means for generating a time varying electric field having a first frequency which is lower than a Larmor frequency of said object; and
 - means for successively applying said time varying electric field between pairs of diametrically opposed wires at a second spatial frequency, said second spatial frequency being much less than said first frequency;
 - wherein said time varying electric field produces a linear magnetic field gradient in said object.
2. An apparatus as set forth in claim 1, wherein said wire conductors are arranged in a bird cage configuration that is tuned to said Larmor frequency.
3. An apparatus as set forth in claim 1 or 2, further comprising:
 - means for generating RF fields having a frequency centered near said Larmor frequency; and
 - means for applying said RF fields to said conductive wires;
 - wherein said RF fields become circularly polarized and rotate about said conductive wires.
4. An apparatus as set forth in claim 1, 2, or 3, further comprising:
 - a first set of filters connected on said first ring conductor between said conductive wires for tuning said conductive wires near said Larmor frequency; and
 - a second set of filters connected between said applying means and said first ring conductor for passing through said first frequency and for filtering out said Larmor frequency.
5. An apparatus as set forth in any one of claims 1 to 4, wherein said conductive wires detect signals generated by said object and said apparatus further comprises means for processing the detected signals in order to produce an image of said object.
6. An MRI apparatus for producing an image of an object, comprising:
 - means for producing a homogeneous magnetic field along a first axis;
 - means for generating a first modulated voltage having a first frequency that is equal to a Larmor frequency, said Larmor frequency being specified by said homogeneous magnetic field and by said object;
 - means for generating a second modulated voltage having a second frequency that is less than said first frequency;
 - means for receiving said first voltage and said second voltage and for generating a first electric field and a second electric field respectively having said first frequency and said second frequency;
 - control means for selectively applying said first voltage and said second voltage to said receiving means; and
 - means for detecting signals emitted by said object after the application of said first voltage and said second voltage;
 - wherein said second electric field produces a linear magnetic field gradient in said object and said

control means further comprises means for processing the detected signals to generate an image.

7. An MRI apparatus as set forth in claim 6, wherein said means for generating said first and second electric fields comprises:
 - 5 a plurality of conductive wires arranged in parallel to each other and formed in a shape of a cylinder;
 - a first ring conductor for joining said conductive wires at one end of said conductive wires; and
 - a second ring conductor for joining said conductive wires at an end opposite said one end of said conductive wires;
 - 10 wherein said first electric field rotates about said conductive wires at said Larmor frequency and said second electric field rotates about said conductive wires at a third frequency that is much less than said second frequency.
8. An MRI apparatus as set forth in claim 6 or 7, wherein said means for generating said first and second electric fields is also said detecting means.
9. An MRI apparatus as set forth in claim 6, 7 or 8, wherein said processing means uses a projection reconstruction technique to produce said image of said object.
- 20 10. An MRI apparatus as set forth in any one of claims 6 to 9, wherein said processing means employs at least one look up table containing Bessel functions when processing said detected signals to produce said image of said object.
- 25 11. An MRI apparatus as set forth in any one of claims 6 to 10, wherein said processing means employs at least one look up table containing solutions to Sommerfeld's integral when processing said detected signals to produce said image of said object.
- 30 12. An MRI apparatus as set forth in any one of claims 6 to 11, wherein said detecting means detects said signals when said second voltage has a first polarity and detects said signals when said second voltage has a polarity opposite said first polarity and said control means adds said signals detected at opposite polarities together to thereby cancel an error component in said signals.
- 35 13. An MRI apparatus as set forth in any one of claims 6 to 12, wherein said detecting means detects said signals when said second voltage has a first polarity and detects said signals when said second voltage has a polarity opposite said first polarity and said control means subtracts said signals detected at opposite polarities to determine an error component in said signals, said error component being used for controlling a quality of said image.
- 40 14. A method for generating magnetic field gradients for use in magnetic resonance imaging of an object, comprising the steps of:
 - arranging a plurality of conductive wires in parallel to each other in a shape of a cylinder;
 - joining said plurality of conductive wires with a first ring conductor at one end of said conductive wires;
 - joining said plurality of conductive wires with a second ring conductor at an end opposite said one end of said conductive wires;
 - 45 generating a time varying electric field having a first frequency which is lower than a Larmor frequency of said object;
 - successively applying said time varying electric field between pairs of diametrically opposed wires at a second frequency, said second frequency being much less than said first frequency;
 - 50 wherein said time varying electric field produces a linear magnetic field gradient in said object.
15. A method for generating magnetic field gradients as set forth in claim 14, further comprising the step of tuning said conductive wires to said Larmor frequency.
- 55 16. A method as set forth in claim 14 or 15, further comprising the steps of:
 - generating RF fields at a frequency centered near said Larmor frequency; and
 - applying said RF fields to said conductive wires;
 - wherein said RF fields become circularly polarized and rotate about said conductive wires.

17. A method as set forth in claim 14, 15, or 16, further comprising the steps of:
connecting a first set of filters on said first ring conductor between said conductive wires for tuning said conductive wires near said Larmor frequency; and
connecting a second set of filters between said applying means and said first ring conductor for passing through said first frequency and for filtering out said Larmor frequency.
18. A method as set forth in any one of claims 14 to 17, further comprising the steps of:
detecting signals generated by said object with said conductive wires; and
processing the detected signals in order to produce an image of said object.
19. A method for generating images of an object with magnetic resonance, comprising the steps of:
producing a homogeneous magnetic field along a first axis;
generating a first modulated voltage having a first frequency that is equal to a Larmor frequency, said Larmor frequency being specified by said homogeneous magnetic field and by said object;
generating a second modulated voltage having a second frequency that is less than said first frequency;
receiving said first voltage and said second voltage and generating a first electric field and a second electric field respectively having said first frequency and said second frequency;
selectively applying said first voltage and said second voltage to said receiving means; and
detecting signals emitted by said object after the step of selectively applying said first voltage and said second voltage; and
processing the detected signals and generating an image of said object;
wherein said second electric field produces a linear magnetic field gradient in said object.
20. A method for generating images as set forth in claim 19, further comprising the steps of:
arranging a plurality of conductive wires in parallel to each other in a shape of a cylinder;
joining said plurality of conductive wires with a first ring conductor at one end of said conductive wires;
joining said plurality of conductive wires with a second ring conductor at an end opposite said one end of said conductive wires;
wherein said first electric field rotates about said conductive wires at said Larmor frequency and said second electric field rotates about said conductive wires at a third frequency that is much less than said second frequency.
21. A method as set forth in claim 19 or 20, wherein said step of generating said first and second electric fields is performed by an antenna structure that also performs said step of detecting said signals.
22. A method as set forth in claim 19, 20, or 21, wherein said step of processing uses a projection reconstruction technique to produce said image of said object.
23. A method as set forth in any one of claims 19 to 22, wherein said step of processing employs at least one look up table containing Bessel functions when processing said detected signals to produce said image of said object.
24. A method as set forth in any one of claims 19 to 23, wherein said step of processing employs at least one look up table containing solutions to Sommerfeld's integral when processing said detected signals to produce said image of said object.
25. A method as set forth in any one of claims 19 to 24, wherein said step of detecting said signals comprises the steps of detecting said signals when said second voltage has a first polarity and when said second voltage has a polarity opposite said first polarity and said step of processing said signals and generating said image comprises the step of adding said signals detected at opposite polarities together in order to cancel out an error component in said detected signals.
26. A method as set forth in any one of claims 19 to 25, wherein said step of detecting said signals comprises the steps of detecting said signals when said second voltage has a first polarity and when said second voltage has a polarity opposite said first polarity and said step of processing said signals and generating said image comprises the step of subtracting said signals detected at opposite

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polarities from each other in order to determine an error component in said detected signals, said error component being used for controlling a quality of said image.

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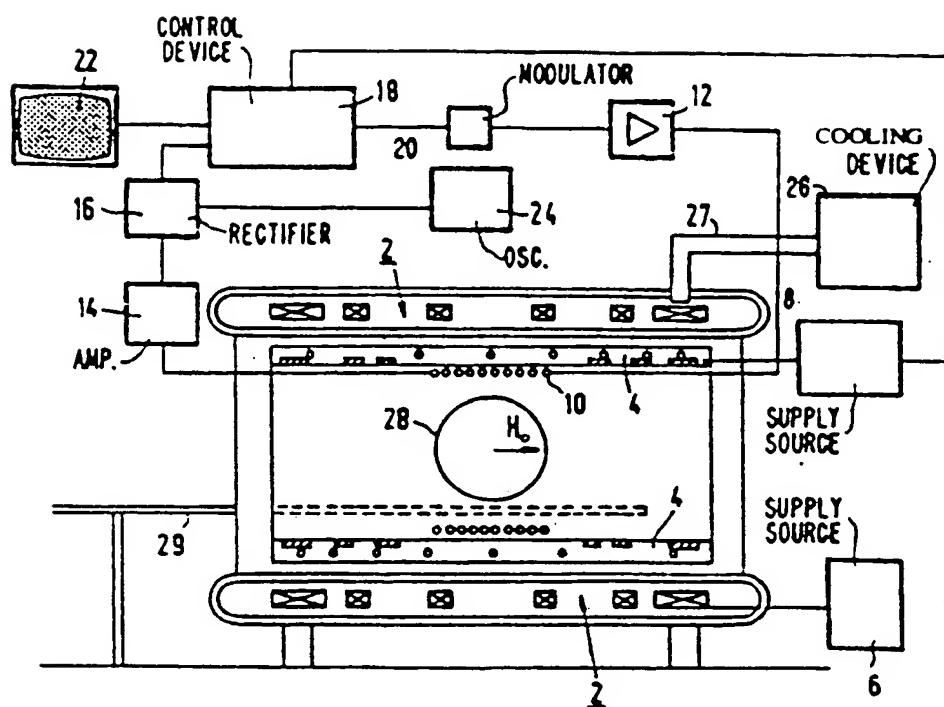


FIG. 1
(PRIOR ART)

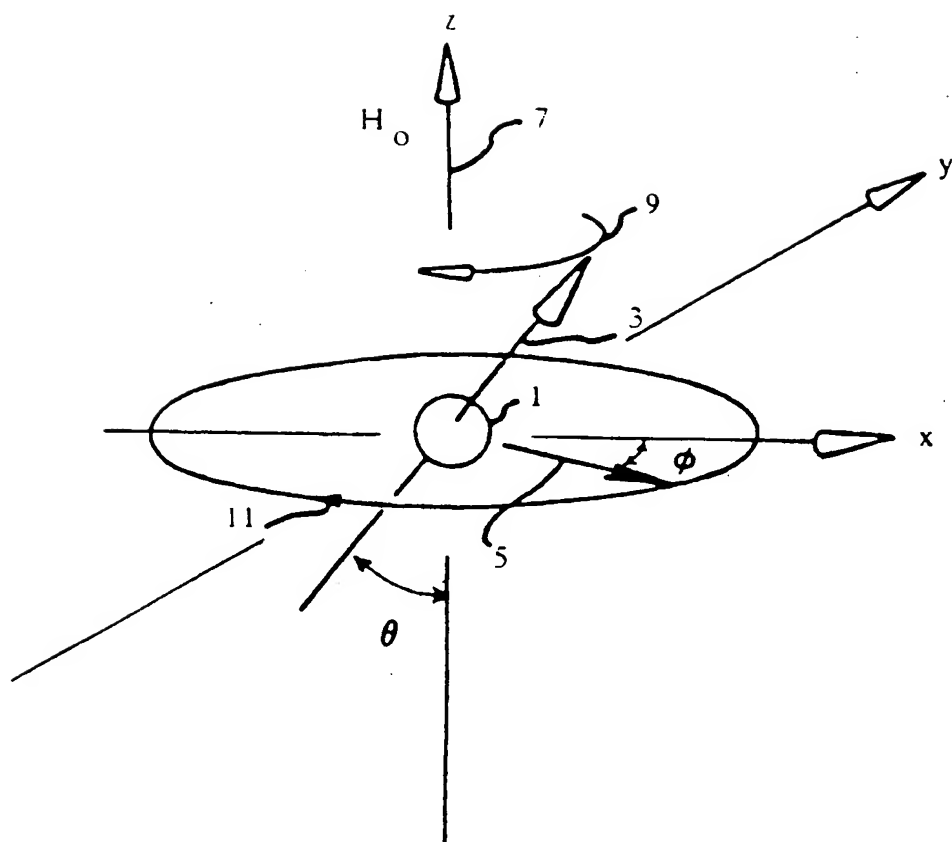


FIG. 3

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